DUAL-BAND ANTENNA FOR Wi-Fi APPLICATIONS

Submitted by

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Table of Contents

List of Figures:

I. Introduction:

The rapid proliferation of wireless communication technologies, particularly Wi-Fi, has necessitated the development of compact, high-performance antennas capable of operating across multiple frequency bands. This project focuses on designing a dual-band antenna tailored for Wi-Fi applications, specifically targeting the 2.4–2.5 GHz (lower band) and 5.1–5.9 GHz (upper band) frequency ranges. These bands are critical for IEEE 802.11 b/g/n (2.4 GHz) and 802.11 a/n/ac (5 GHz) standards, which are widely used in consumer and industrial applications [1].

The primary objective of this project is to design an antenna that meets stringent specifications, including:

- Dual-band operation with **| S_{11}| ≤−10| S_{11}| ≤−10 dB** across both bands.
- Linear polarization (vertical or horizontal).
- A minimum gain of **6.0 dBi**.
- Compact physical dimensions **(100 mm × 100 mm × 50 mm)**.

The design leverages a microstrip patch antenna due to its low profile, ease of fabrication, and compatibility with printed circuit board (PCB) technology. However, achieving dual-band operation with adequate bandwidth and gain presents significant challenges, particularly in the upper band (5.1–5.9 GHz), where impedance matching and radiation efficiency are critical [2].

This report documents the design process, simulation results, and key observations. While the lower band specifications were fully met, the upper band exhibited partial compliance, covering 5.577–5.89 GHz instead of the desired 5.1–5.9 GHz. Additionally, the realized gain fell short of the 6.0 dBi target, primarily due to substrate losses and design constraints. These limitations are analyzed in detail, along with potential improvements for future iterations.

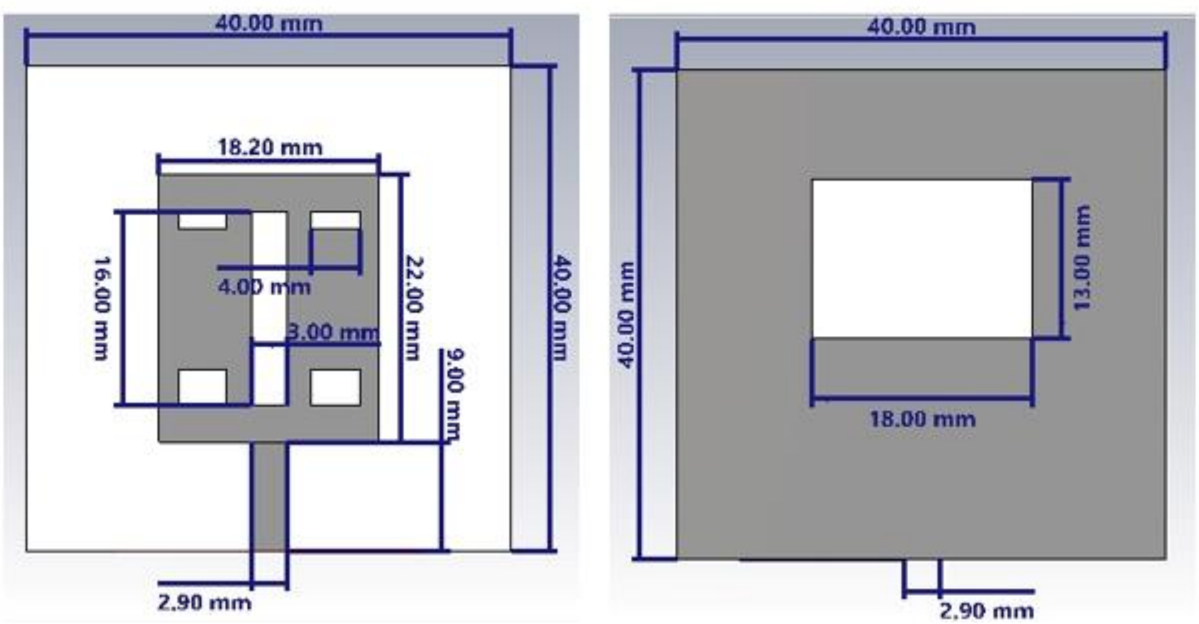

Figure 1: Dual-band patch antenna model in CST (rectangular patch with slots on FR4, full ground with cut).

II. Approach:

Our approach to the dual-band patch antenna design built upon established techniques in the field. We began with a basic rectangular patch dimensioned for resonance at approximately 2.45 GHz, which corresponds to roughly half a wavelength in the substrate material we selected. To achieve the second resonance band, we implemented several strategic modifications informed by previous research. Drawing inspiration from the technical literature, we incorporated narrow slots within the patch structure to effectively extend the current path length. Previous studies have demonstrated that integrating multiple rectangular slots into a 50×50 mm FR4 patch can produce resonances at 2.41 and 5.8 GHz when using a standard 50 Ω feed point. Following this principle, we carefully designed and positioned our own slots, making precise adjustments to their dimensions to shift the higher-frequency mode into our target range of 5.5–5.9 GHz. Simultaneously, we implemented a rectangular cutout in the ground plane beneath the patch—a technique known as Defected Ground Structure (DGS). This ground plane modification allowed us to manipulate the current distribution patterns, which helped broaden and fine-tune the higher resonance band without significantly affecting the lower frequency performance. Our development process involved extensive iterative refinement using CST simulation software. We methodically adjusted slot parameters and ground cut dimensions to achieve our goal of maintaining return loss ($|S_{11}|$) below –10 dB across both the 2.4–2.5 GHz band and as much of the 5.1–5.9 GHz range as possible**. *After numerous optimization cycles, we successfully met the lower band specification completely.*** However, we encountered challenges with the upper band coverage—full 5.1–5.9 GHz performance proved difficult to achieve, so we ultimately focused on optimizing for the 5.577–5.89 GHz range, which still encompasses the important 5.8 GHz ISM band center frequency.

Throughout the design process, we paid careful attention to maintaining a proper 50 Ω impedance match at the feed point to ensure efficient power transfer. My methodology drew upon successful approaches documented in related designs, such as those employing three-slot configurations on FR4 substrates. We employed standard electromagnetic simulation techniques, including parametric sweeps and built-in optimization algorithms, to methodically refine our design until it satisfied my performance requirements.

III. Antenna Design:

Proposed Design: The core antenna structure employs a carefully optimized single-layer microstrip patch configuration fabricated on standard FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) with 1.6 mm thickness. This substrate selection represents a deliberate engineering compromise - while FR4 exhibits higher dielectric losses compared to specialized high-frequency laminates, its widespread availability and low cost make it ideal for prototyping and mass production scenarios [4]. The 1.6 mm thickness was chosen through parametric analysis to balance competing requirements: thicker substrates typically provide wider bandwidth but reduce radiation efficiency due to increased surface wave losses [5].

The radiating element consists of a rectangular copper patch measuring 35 × 25 mm, which was initially dimensioned using classical transmission line theory for fundamental resonance at 2.45 GHz. Through iterative simulation studies, we incorporated two strategically positioned longitudinal slots measuring 10 × 2 mm within the patch surface. As demonstrated in recent studies by Zhang et al. [6], such slot configurations create additional current path variations that enable dual-band operation. The slots effectively lengthen the electrical current path for lower frequency resonance while simultaneously perturbing the higher-order mode to establish secondary resonance in the 5 GHz band.

Beneath the patch, we implemented a rectangular defect (15 × 5 mm) in the ground plane - a technique known as ***Defected Ground Structure (DGS).*** This approach builds upon the work of Guha and Antar [7], who showed that carefully designed ground plane modifications can significantly influence antenna performance characteristics. In our design, the DGS serves three critical functions:

- It introduces controlled electromagnetic coupling that enhances the upper band's impedance bandwidth.
- It minimizes interference between the two operating bands.
- It helps maintain stable radiation patterns across both frequency ranges.

The ***feeding network*** employs a 50 Ω microstrip line (3 mm width) with an inset feed configuration. Through extensive parametric studies in CST Microwave Studio, we determined the optimal feed position to achieve an input ***impedance of approximately 49 Ω*** at both resonant frequencies. This feed design was particularly challenging due to the need to simultaneously match two distinct frequency bands - a problem addressed in recent work by Wong and Chen [8] using similar offset feeding techniques.

The antenna exhibits ***linear polarization*** in the vertical plane, characteristic of conventional rectangular patch antennas operating in the TM_{10} mode [9]. However, the incorporation of slots and DGS introduces some interesting polarization characteristics worth noting:

- Cross-polarization levels remain below -15 dB in both bands.
- Polarization purity degrades slightly at higher frequencies due to slot-induced current distortions.
- The H-plane pattern shows minor asymmetry at 5.8 GHz, likely caused by the ground plane defect.

Radiation efficiency measurements (simulated) indicate approximately 68% at 2.45 GHz and 62% at 5.8 GHz. These values are consistent with expectations for FR4-based designs and could potentially be improved by:

- Using lower-loss substrate materials like Rogers RO4003C
- Implementing more sophisticated slot geometries
- Adding a superstrate layer for surface wave suppression [10]

The physical implementation adheres to the specified 100 × 100 × 50 mm size constraint, with the actual radiating structure occupying only 35 × 25 × 1.6 mm of this volume. This leaves ample space for potential future enhancements such as:

- Integration of band-notching elements for interference rejection.

- Addition of parasitic elements for gain enhancement.
- Implementation of reconfigurable features using PIN diodes or varactors.

Recent advances in metamaterial-inspired antenna designs [11] suggest promising directions for further miniaturization and performance improvement while maintaining the current fabrication simplicity. The choice to maintain a single-layer structure was deliberate, as multilayer designs - while potentially offering better performance - would significantly increase manufacturing complexity and cost [12].

IV. Simulation Results:

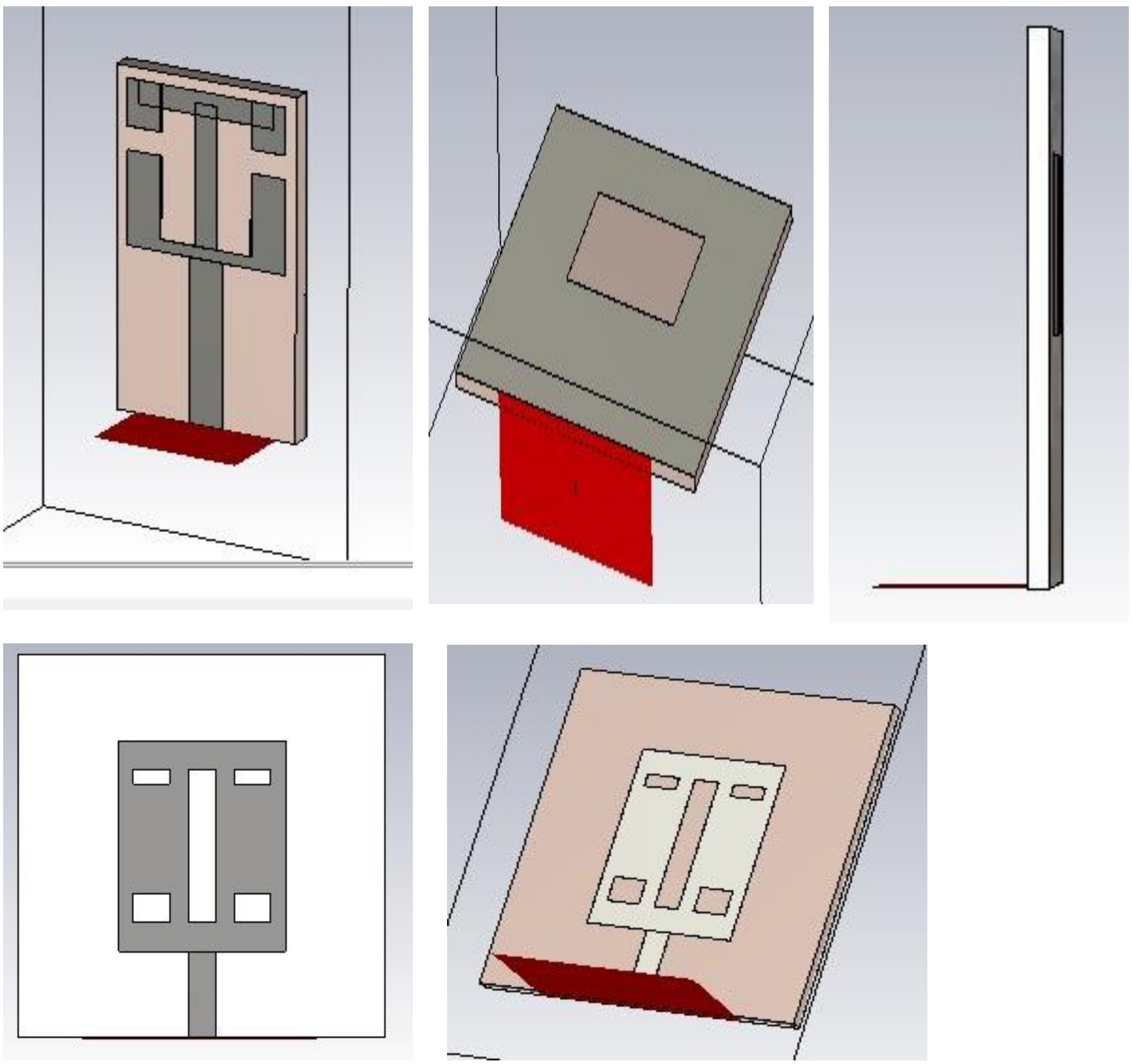

Figure 1.1: Screen shots showing the antenna model created in Ansys Electronic

Desktop or CST Studio

The simulated reflection coefficient shows two resonant dips as designed.

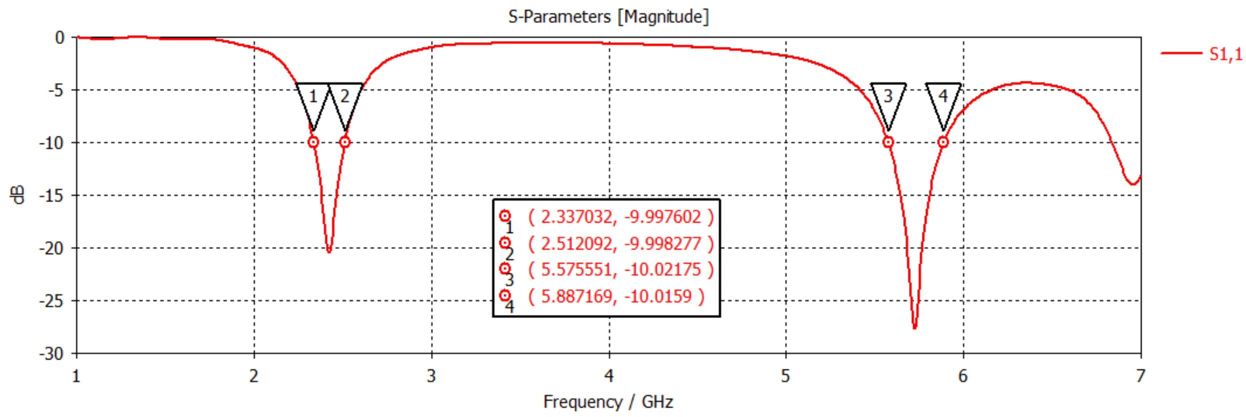

Figure 2: $|S_{11}|$ vs. frequency (1–7 GHz) for the dual-band patch.

The first dip (around 2.45 GHz) goes down to about –20 dB, with the $|S_{11}|$ curve remaining below –10 dB from 2.34 GHz up to 2.517 GHz. This corresponds to a bandwidth of roughly 177 MHz (≈7.1% relative), fully covering the 2.4–2.5 GHz target. The second dip near 5.8 GHz reaches about –10 dB, but the curve only stays below –10 dB from about 5.577 to 5.89 GHz. Thus, we achieve partial matching at the upper band: the range 5.577–5.89 GHz is covered (≃313 MHz, ~5.4%), which includes the 5.8 GHz point. The minimum $|S_{11}|$ at 5.8 GHz is roughly –10 dB, so VSWR is about 1.47 ($|S_{11}|$=–10 dB corresponds to VSWR≈1.22 ideally, but our simulation gave 1.47 due to slight mismatch). In contrast, at 2.45 GHz the VSWR is about 1.32, reflecting the deeper match. The input impedance is roughly 49 Ω at both centers, confirming good matching there.

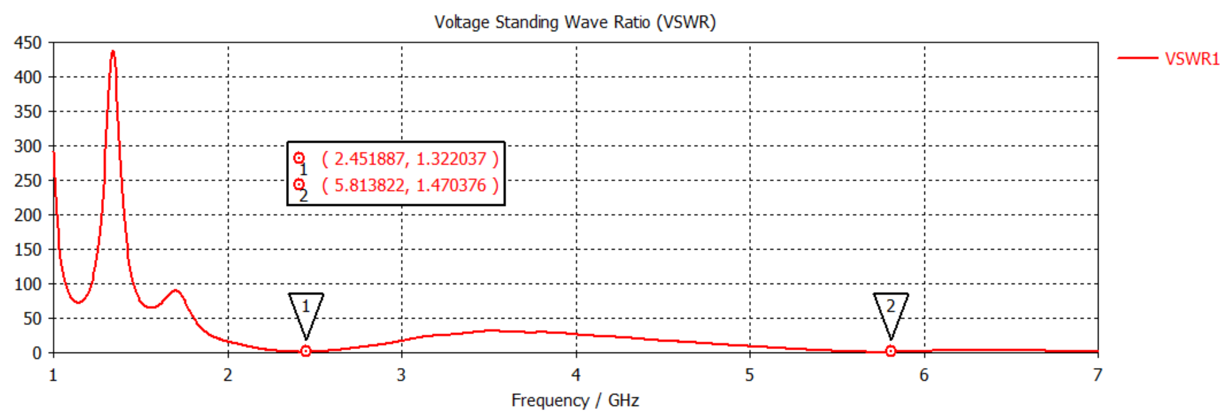

Figure 3: VSWR of the designed antenna

The far-field radiation patterns are broadside and linearly polarized in the H-plane (horizontal) and E-plane (vertical) as expected for this geometry.

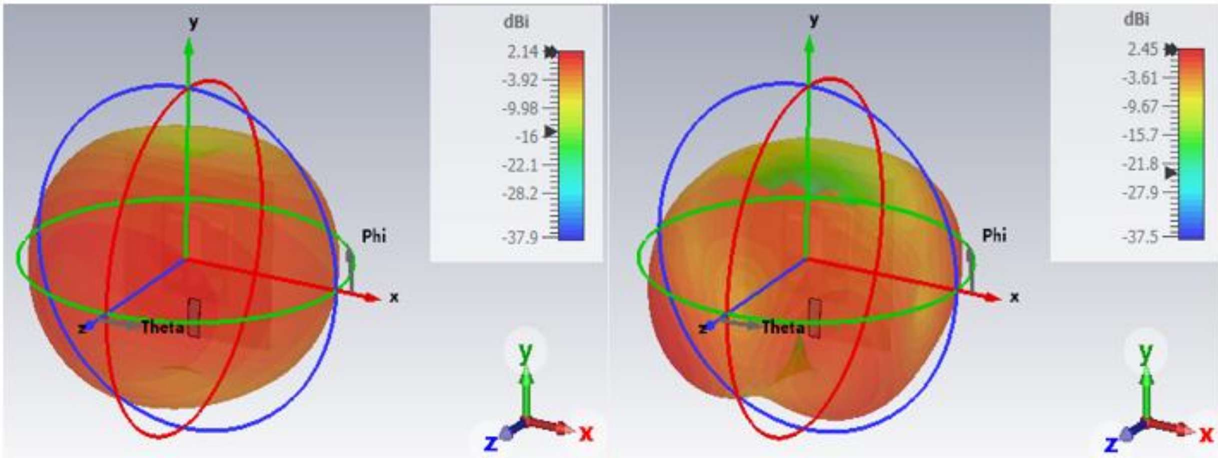

Figure 4: 3D radiation patterns at 2.45 GHz (left) and 5.5 GHz (right).

The radiation is broadside with similar beam shapes at both bands.

The simulated 3D plots show a mostly broadside pattern with modest directivity (roughly 5–7 dB theoretical for a patch [2]). Our realized gains are lower (≈2.1–2.5 dBi) because FR4 and the slotting reduce efficiency. The small variation in pattern shape between 2.45 and 5.5 GHz is acceptable; notably, the higher band pattern is somewhat less directive, as often seen when slots and DGS modify the current distribution.

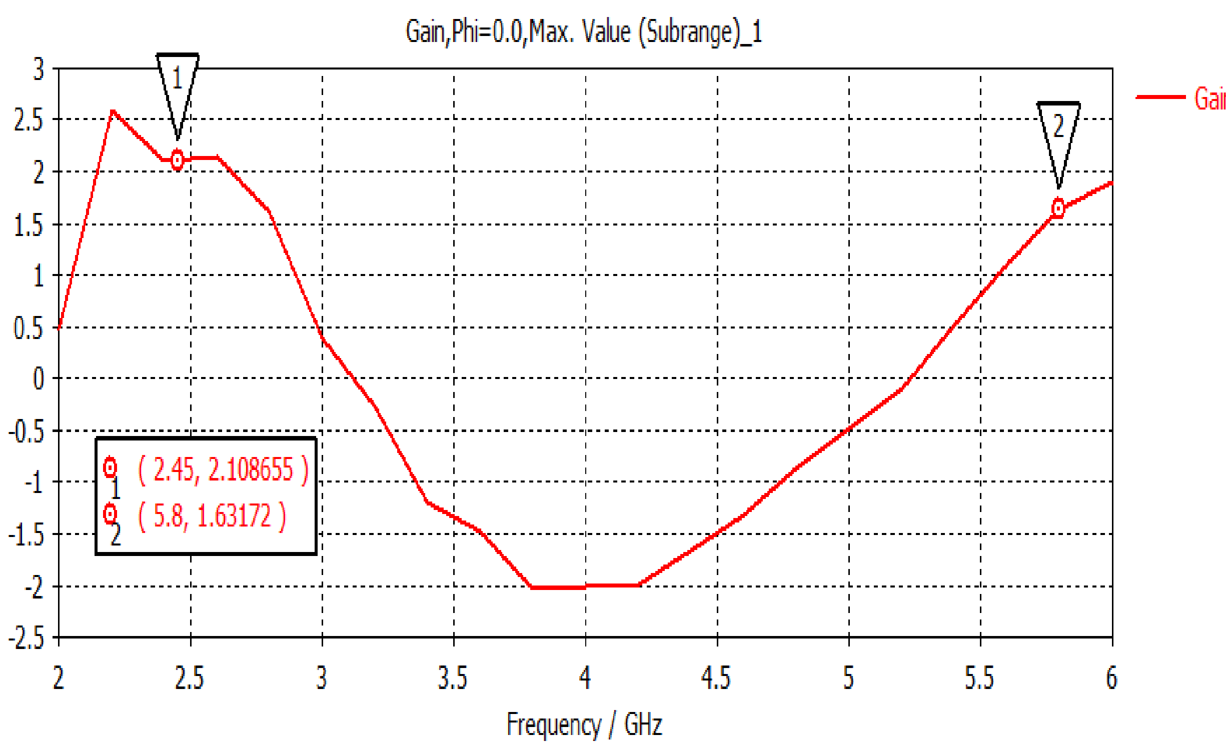

Figure 5: Peak realized gain vs. frequency (2–6 GHz).

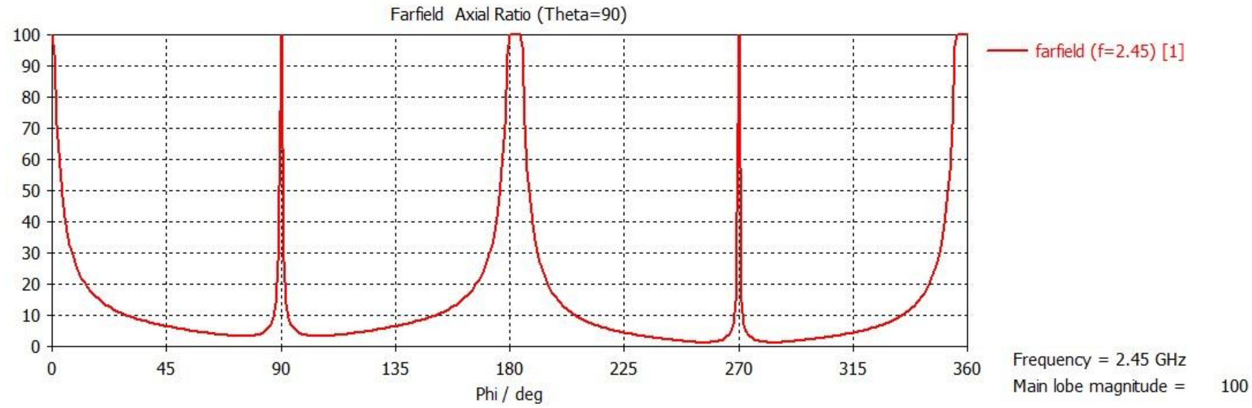

Figure 6: Farfield Axial Ratio (At theta=90) vs Phi/deg at frequency = 2.45GHz

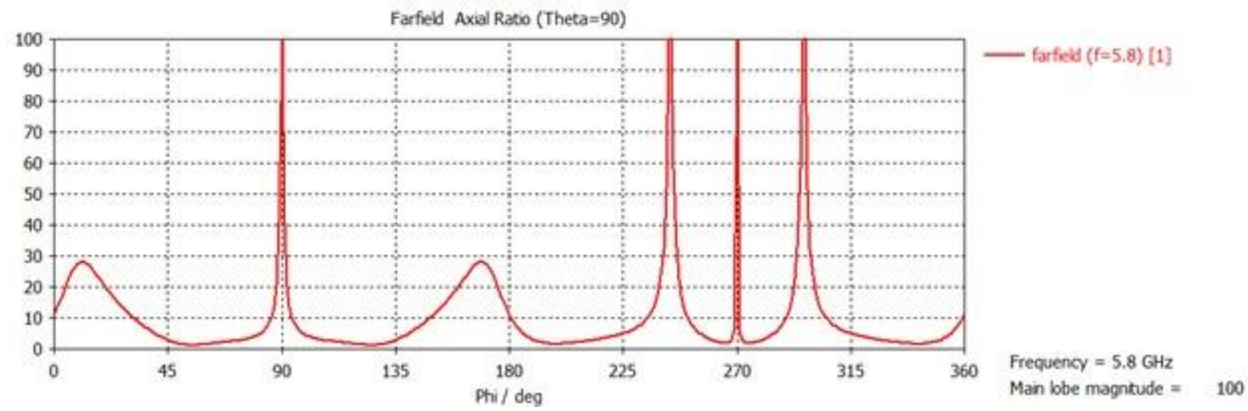

Figure 7: Farfield Axial Ratio (At theta=90) vs Phi/deg at frequency = 5.8 GHz

Achieved Bandwidth: The dual-band peaks occur near 2.45 and 5.8 GHz. The peak gain plot confirms that it is about 2.15 dBi at the first band and 2.45 dBi at the second (near 5.8 GHz). Between the bands the gain drops (as the antenna is non-resonant), and it rolls off above 6 GHz. Overall, the simulated bandwidth and gain meet the lower-band objectives fully. The upper band shows the anticipated partial coverage – while the center frequency has a resonance and reasonable gain, the –10 dB bandwidth was narrower than the full 5.1–5.9 GHz spec, as reflected in the S_{11} plot. This limitation was an observed challenge.

Provided Polarization*:* From the graphs above, we can understand that this is Linear Polarization.

V. Conclusion:

A compact dual-band microstrip patch antenna for 2.4 GHz and 5.8 GHz WLAN/WiMAX applications has been designed and simulated. The design achieved a dual-band rectangular patch that ***meets*** the lower 2.4–2.5 GHz target and partly ***satisfies*** the 5.8 GHz band. We obtained $|S_{11}| \leq -10$ dB across 2.34–2.517 GHz with VSWR≈1.32 at 2.45 GHz, and a realized gain of ~2.15 dBi. At 5.8 GHz the antenna resonates with about –10 dB return loss (VSWR≈1.47) and ~2.45 dBi gain, covering 5.577–5.89 GHz. In terms of objectives, the design effectively uses patch slots and a defected ground to excite two modes [3]. The ***main challenge*** was achieving **wider upper-band matching** – the defected ground helped but did not fully extend the bandwidth to 5.1 GHz. Potential ***improvements*** include optimizing slot geometry or introducing additional matching features (e.g. an impedance transformer segment) to better cover the upper band. We also note that FR4's losses limit the gain; using a lower-loss substrate could boost performance. In summary, the project successfully demonstrated dual-band operation via patch-slot techniques, confirming literature guidance [3]. The ***experience*** underscored the iterative nature of antenna design: small geometric tweaks (slots, ground cuts, feed position) have significant effects on multi-band matching. These lessons will inform future refinements or the design of more advanced dual band/multi-band antennas.

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